Preprint
UCRL-JC-149978

Amplitude Control of Solid-State Modulators for Precision Fast Kicker Applications

J.A. Watson, R.M. Anaya, G.C. Caporaso, Y.J. Chen, E.G. Cook, B.S. Lee, S.A. Hawkins

This article was submitted to
Recent Progress in Induction Accelerators Workshop,
Tsukuba, Japan, October 29-31, 2002

U.S. Department of Energy
Lawrence Livermore National Laboratory

November 15, 2002

AMPLITUDE CONTROL OF SOLID-STATE MODULATORS FOR PRECISION FAST KICKER APPLICATIONS

J.A. Watson, R. M. Anaya, G. C. Caporaso, Y.J. Chen, E.G. Cook, B.S. Lee, S.A. Hawkins

Lawrence Livermore National Laboratory

Abstract

A solid-state modulator with very fast rise and fall times, pulse width agility, and multi-pulse burst and intra-pulse amplitude adjustment capability for use with high speed electron beam kickers has been designed and tested at LLNL. The modulator uses multiple solid-state modules stacked in an inductive-adder configuration. Amplitude adjustment is provided by controlling individual modules in the adder, and is used to compensate for transverse e-beam motion as well as the dynamic response and beam-induced steering effects associated with the kicker structure. A control algorithm calculates a voltage based on measured e-beam displacement and adjusts the modulator to regulate beam centroid position. This paper presents design details of amplitude control along with measured performance data from kicker operation on the ETA-II accelerator at LLNL.

1 Introduction

High-speed beam kickers are used to provide precision beam manipulation for high current electron beams. This technology has been demonstrated on the ETA-II accelerator at LLNL. The kicker system is a fast dipole driven by sharp risetime modulators to provide precision manipulation of high current (order kA) electron beams. The kicker is similar in design to a stripline beam position monitor. There are four equal size electrodes enclosed within a vacuum housing, as shown in figure 1.

An opposite pair of electrodes is driven by fast modulators through transit time isolated cables to provide a vertical (or horizontal) kick to the beam. This kick is translated into a displacement as the beam passes through a drift space following the kicker. The other two electrodes are terminated at both ends. The output pulse

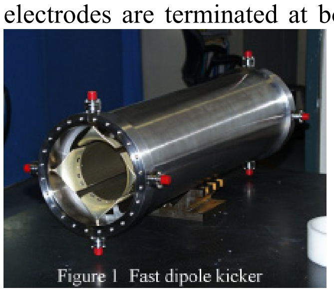


Figure 1 Fast dipole kicker

width of the modulators are adjustable, to provide control of dose level in radiographic applications. In this instance, a DC bias dipole magnet is wound over the kicker and is on at all times to deflect the beam into a dump. When an x-ray pulse is desired the modulators activate and overcome the bias dipole force allowing the beam to steer straight ahead through the rest of the transport section and on to the converter target.

Additionally, the modulators are capable of supplying a burst of pulses, as shown in figure 2, for multi-pulse radiographic applications.

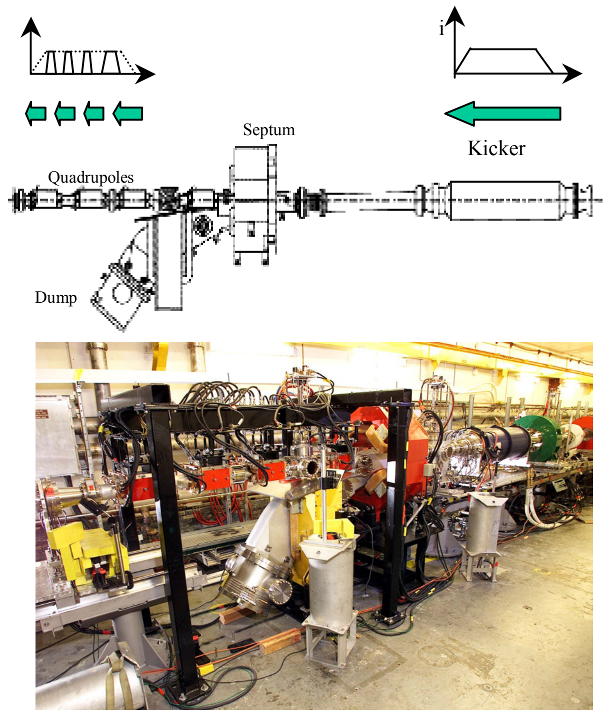


Figure 2 Kicker and associated transport elements

2 The Modulators

The modulators are linear inductive adders, essentially a stack of transformers with the secondaries connected in series. The primary and secondary winding of each stage consists of a single turn. MOSFETS are used to switch energy stored in a

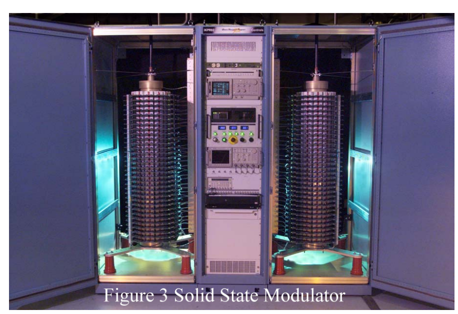


Figure 3 Solid State Modulator

capacitor into the primary of each transformer. As illustrated in figure 4, the conduction interval of each stage is controlled by the width of the pulse on the drive

This work was performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48

circuit of the device, allowing for variable pulse width and burst capability [2]. The output voltage is scaleable, simply by adjusting the number of stages in the adder. We have achieved voltages in excess of 50kV with this approach. For ETA-II, the nominal operating voltage is 4 – 8kV. Amplitude control is accomplished by controlling individual stages in the adder structure. Some of the boards are charged to one half or one fourth of the nominal charge voltage to achieve fine voltage control. The system is essentially a high voltage, ultra-high speed D/A converter. While the turn-on time of the adder assembly is extremely fast (approaching 20kV in 10nS), articulation of the amplitude is much more difficult as each modulation stage must switch the full output current of nearly 400A. We have achieved slew rates of over 50,000 V/µSec (linear ramp) using this approach.

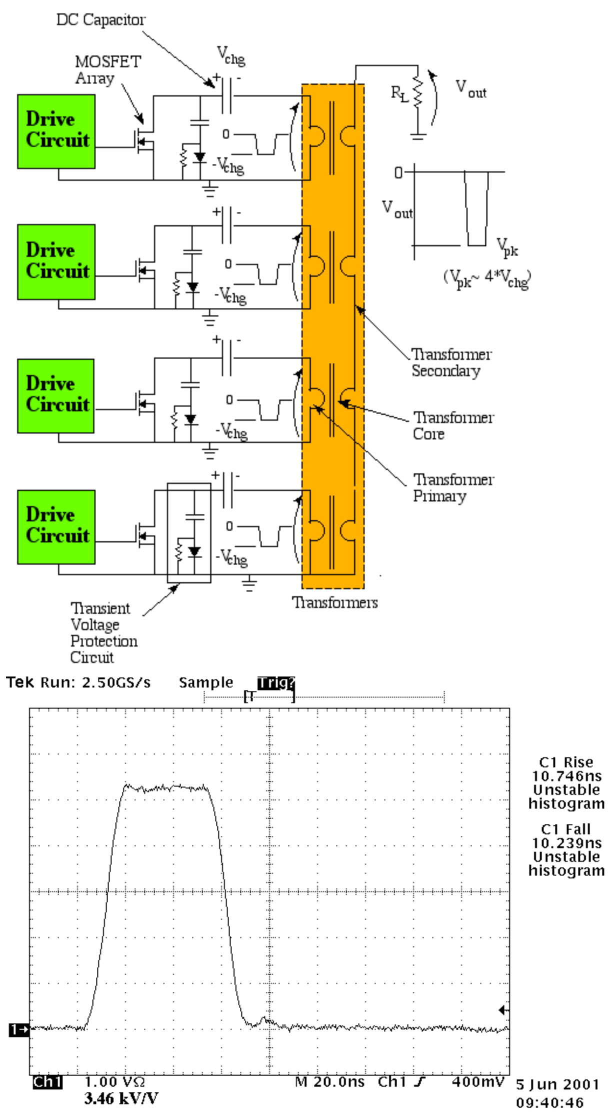


Figure 4a, b Solid-state modulator block diagram and typical output waveforms into 50 ohms

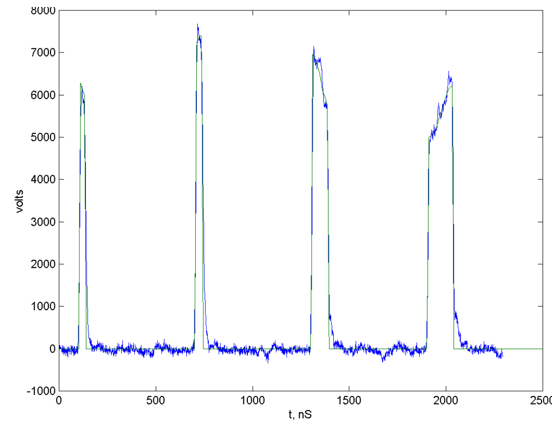


Figure 4c Desired and measured modulator voltage for a 4-pulse burst

3 Control System

The control system used to determine the desired modulator output voltage to be applied to the kicker utilizes a feedforward design whereby the calculated voltage is based on information from current and past iterations. The beam is not actively controlled as it passes through the kicker; rather the voltage applied to the kicker is calculated based on the measured position of the beam on the previous pulse. Equation (1) shows the relationship between electron beam displacement through the kicker and the applied voltage. A more detailed treatment can be found in [1] and [4]. If we assume negligible beam-induced steering effects, we have a solution to the differential-integral equation of the kicker as a function of time:

$$x(z=l,t)=\frac{c^2}{4V_0 l}\int_{t-2l/c}^{t} V_p(t')(t-t')dt' \qquad (1)$$

where $V_p(t)$ is the applied voltage and c is the speed of light. The correction in deflection due to time-varying modulator waveform at the i-th iteration is:

$$\begin{aligned}\Delta x(t) &= x_{desired} - x^{i-1}(t) \\ &= \frac{c^2}{4V_0 l}\int_{t-\frac{2l}{c}}^{t} \Delta V_p(t')(t-t'+\frac{2d}{c})dt'\end{aligned} \qquad (2)$$

where $\Delta X(t)$ and $\Delta V_p(t)$ can be expressed as polynomial series:

$$\Delta x(l,t) = \sum_{n=0}^{N} \Delta x_n t^n \qquad (3)$$

$$\Delta V_p(t) = \sum_{n=0}^{N} \Delta V_n t^n \qquad (4)$$

By plugging (3) and (4) back into (2) and collecting like terms, we derive a one-one relationship between ΔX_n and V_n. The Beam Control Algorithm (BCA) compares measured electron beam position at the kicker exit to a desired setpoint ($X_{desired}$) and calculates a desired waveform (V_n) to be applied to the kicker. An order N=8 was found to provide sufficient fidelity to correct for variation in beam motion on the ETA-II accelerator. The BCA is iterative and adaptive, and can correct for effects that are deterministic but not correctly estimated by (1), including beam-induced steering and the impedance characteristics of the kicker structure.

4 Digital Control of the Modulators

Control of individual stages of the modulators is provided by aTektronix® AWG520 10 bit Digital Pattern Generator, running at 1nS/step. A second, iterative control algorithm is nested within the beam control algorithm, and forces the actual output of the modulators (measured at the kicker) to match the desired waveform from the BCA. This inner loop is referred to as the Pulser Control Algorithm (PCA). The PCA uses a simple gradient projection algorithm (5) to adjust the loop gain on each iteration and provide optimal convergence while maintaining stability.

$$\hat{\theta}(k) = \hat{\theta}(k-1) + \frac{\beta\, y(k)y(k-1)}{c + y(k-1)^2} \qquad (5)$$

The control law is implemented as follows:

$$u(k) = u(k-1) + (\hat{\theta}(k) - \alpha)y(k) \qquad (6)$$

where u(k) is the control effort applied (loop gain), and y(k) is the error signal. β and α are constants.

The conduction interval of the MOSFET switches used in the modulators is not linearly related to the width of the gate drive pulse for narrow pulses due to characteristics inherent with the devices. Figure 6 shows the relationship between output pulse-width to input (gate) pulse-width for a typical stage. For pulses under about 18nS, the devices do not turn on at all. Lookup tables are used to match the modulator output pulse-width to the desired pulse-width for narrow pulses. For pulses between 20 – 40nS, the peak amplitude of the desired output pulse is set by turning on additional stages in the adder with the same pulse-width as the main portion of the modulator i.e. the peak amplitude of the pulse is set to the desired level. For pulses between 41 – 120nS, the PCA matches the output pulse amplitude on a point-by-point basis (at 1nS per point) with the desired voltage.

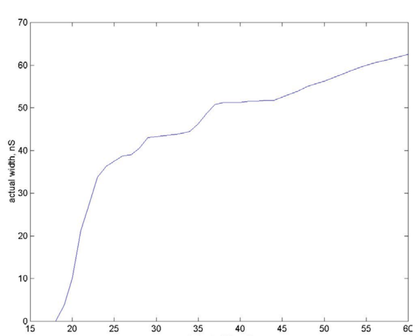


Figure 6 MOSFET switch output pulse-width versus desired width

5 Performance

In normal operation, the kicker is operated with a dipole surrounding the structure to steer the beam off center and ultimately into the dump. Energizing the kicker overcomes the dipole field and the kicked portion of the beam is transported straight ahead. To transport the full beam on ETA-II, this dipole was simply turned off with the kicker un-energized. Additionally, the transport element spacing tested on ETA-II was designed for a 20MeV application. To reduce space charge effects of the lower energy (6MeV) ETA-II accelerator, the beam was transported through an aperture ahead of the kicker to lower the current from 2kA to approximately 200A. The nominal beam deflection at the entrance to the septum was approximately 4cm. The quadrupole septum magnet used downstream of the kicker separates the kicked and unkicked beams into a transport line and beam dump, respectively, as shown in figure 2. The length of the kicker structure and the risetime of the modulators determine the beam-switching time. Figure 7 shows beam position at the kicker exit (septum entrance), overlaid with the beam current transported past the septum.

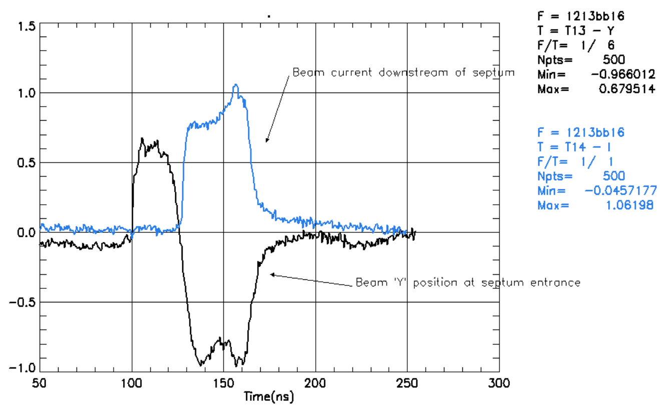


Figure 7 Kicker switching time. Beam current is 100A/div and position is 0.5cm/div

Figure 8 shows the same kicked pulse as in figure 7, overlaid with the full, unkicked ETA-II beam (dipole surrounding the kicker is off).

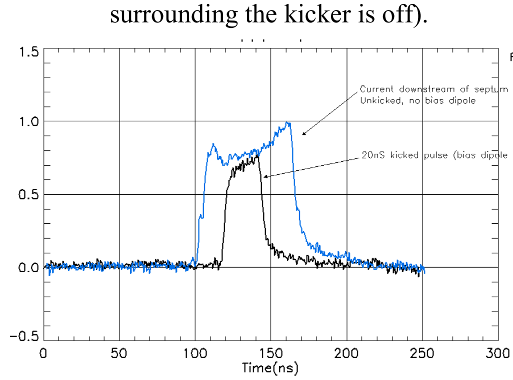


Figure 8 Measured beam current on ETA-II for a full and 20nS-wide kicked beam (100A/div)

Convergence of the beam control algorithm is dependent on several factors, including repeatability of the accelerator and the amplitude of transverse motion on the incoming beam. To evaluate the amplitude modulation capability, a 41nS wide pulse was applied to the kicker on ETA-II. Figure 9 shows unkicked and kicked beam position measured downstream of the kicker, along with the applied voltage on the kicker. The system converged to ± 1mm of the desired beam position setpoint in three iterations (three beam shots). Note that with the exception of the head and tail of the beam, the control system corrected for transverse motion (intentionally introduced corkscrew motion) of the incoming beam. To achieve this precision level of beam position regulation, the modulators and associated controls were required to match the desired output voltage to within ± 1.5%.

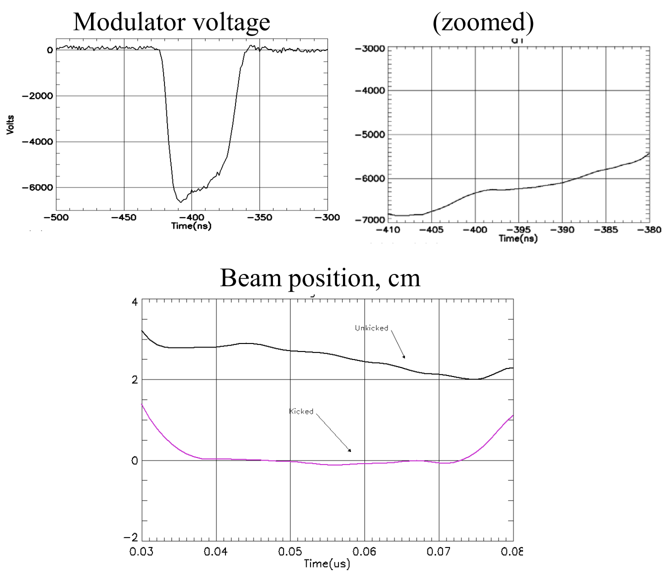
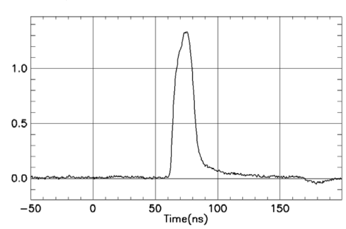


Figure 9 Unkicked and kicked beam position

A consequence of switching beams with kickers is spot-size dilution due to the switching time. This is the apparent "blurring" of the beam profile downstream of the kicker. The effect is most apparent for very narrow kicked portions of the beam, as the dwell time of the beam at its' nominal (kicked) position is essentially zero. Figure 10 shows beam current past the septum with a narrow pulse (approx. 18nS FWHM) applied to the kicker. Also shown are time-integrated images of the beam profile for the kicked and unkicked (full width beam) case.



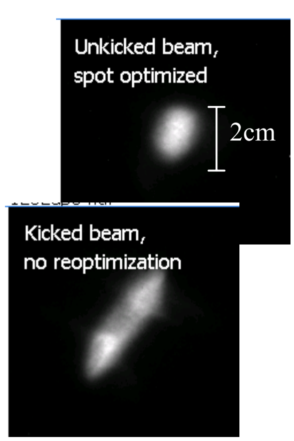
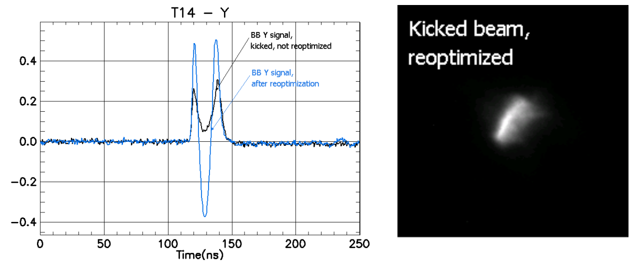


Figure 10 Narrow kicked beam(100A/div), and time integrated images of the beam after the kicker.

We found an optimized tune for the transport elements downstream of the septum that minimized the slewing of the kicked beam. Figure 11 shows measured beam deflection with the baseline and optimized transport tunes.



7 Conclusion

We have demonstrated that solid-state modulators with intra-pulse amplitude modulation capability driving fast kickers can provide precision manipulation of high current beams. The associated control system can compensate for transverse motion in the incoming beam (provided the motion from head-tail is repeatable on subsequent shots), as well as the dynamics associated with the kicker structure. Additionally, we have found optimal transport element tunes to minimize slewing of the kicked beam.

6 References

[1] Y.J. Chen et al. "Precision fast kickers for kiloampere electron beams" 1999 Particle Accelerator Conference, New York, NY

[2] Ed Cook, et al. "Inductive-adder Kicker Modulator for DARHT 2" Linac2000, Monterey, CA

[3] J. Watson, et al. "A Solid'State Modulator for High Speed Kickers" Particle Accelerator Conference 2001, Chicago, IL

[4] Y.J. Chen "Notes on the Kicker Control System" USPAS 2000W, Tucson, AZ